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13. ABSTRACT *(Maximum 200 words)*

A summary of the results obtained in research sponsored by the Army Research Office under contract DAAL03-92-C-0018 and conducted during the period July 1, 1992 to August 31, 1995 is presented. Reliable data distribution within spread-spectrum packet radio networks requires high performance from the network protocols. The high variability of the qualities of the links and the unique characteristics of frequency-hop spread-spectrum signaling impose special requirements for network protocols that are to be employed in frequency-hop packet radio networks. Side information that can be extracted from the received spread-spectrum signals that are embedded in noise and interference provides information about the quality of the links in the packet radio network. This research investigated several techniques for utilizing side information to aid the network protocols in establishing reliable routes in a mobile, tactical packet radio network.

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Use of Side Information in Adaptive Protocols for Spread-Spectrum Packet Radio Networks

Final report

Harlan B. Russell

For the period July 1, 1992 to August 31, 1995

U.S. Army Research Office

Contract Number DAAL03-92-C-0018

Techno-Sciences, Inc.
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Statement of the problem studied

Techno-Sciences, Inc., has demonstrated significant improvements in the performance of frequency-hop packet radio networks through innovative designs for the forwarding and routing protocols. These protocols have been designed and simulated as part of a TSI project which is funded by the Army Research Office under an SBIR Phase II contract.

TSI has focused its research on network protocols for mobile packet radio networks that can adapt to a hostile environment, use decentralized control, and have a distributed organization. Mobile radio networks will often require a packet to travel over multiple hops to reach its destination and the radios in the network must be able to store and forward packets. Reliable data distribution within mobile packet radio networks requires not only good performance from the elements that make up the individual links but also good performance from the network protocols that are needed to establish and maintain a survivable network.

Summary of the most important results

TSI has developed new forwarding and routing protocols that are specifically designed for frequency-hop packet radio networks. The performance improvements gained from the link and network layer protocols are made by exploiting the special characteristics of frequency-hop spread-spectrum signaling and the requirements of a multiple-hop packet radio network.

Least resistance routing (LRR)

The LRR protocol is an adaptive, decentralized, distributed routing protocol that accounts for multiple-access and partial-band interference at each of the radios in a multihop (i.e., store-and-forward) network. Each radio maintains a measure of its own reception quality for packets coming from each of its neighbors. The link resistance is a measure of the reliability of the link, and the metrics used to quantify this reliability must be consistent with the characteristics of the despreading, demodulation, processing, and decoding subsystems in the radio receiver. In general, the metric must account for the influence on the packet error probability of the amount of power in the received signal, the receiver noise density, and the interference at the receiver.

TSI has designed metrics that provide a quantitative measure of each link's ability to provide reliable communication. The metrics account for the net effects of partial-band, multiple-access, and narrow-band interference without having to discriminate between these interferences sources or respond to them individually. Upon receiving a transmission, side information available from the decoder provides information about the quality of the channel as seen by the FH receiver. This information is used to set a resistance for that link. The lower the resistance for a link, the higher the probability of success for packets that are transmitted over that link. The different sets of links that connect each pair of radios are compared, and the path with the least total resistance is selected as the preferred route.

We have shown that the forwarding and routing protocols that we have designed can greatly improve the network performance when knowledge of the interference environment is used. Pursley has presented results on a number of methods to gather side information and has shown how side information can be used to improve the packet decoding probability. Side information provides very effective information about the interference environment that can be used in the network protocols to improve the throughput.

Least resistance routing has been examined in a simulation of a FH packet radio subnetwork that includes the effects of mobile radios, link failures, multiple-access interference and jamming. Comparisons have been made between LRR and tier routing, a routing method devised as part of the SURAN program. We have found that LRR identifies and responds quickly to changes in the link quality whether from interference or mobility, and is effective in choosing routes that avoid regions of the network that have excessive interference. Also, the resistance values used by LRR provide more information about the probability of success for a transmission than is provided in tier routing. We have found that side information on the number of errors and erasures in a received transmission provides valuable information about the cause of a poor link. The quality of a link may be poor because of either a high level of multiple-access and partial-band interference or a low received signal-to-noise ratio, or both.

Transmission protocol with reservations

Store and forward packet radio networks often must be able to forward a packet through several radios to be able to deliver the packet to its destination. Forwarding protocols are required to control the relay of packets, and the protocols must account for the high variability of the qualities of the links and the unique characteristics of frequency-hop spread-spectrum signaling. We have investigated one aspect of the forwarding protocol that makes a reservation for a transmission and allows multiple packets to be included in the transmission attempt. The capture property of frequency-hop signaling and the behavior of store and forward packet radio networks are exploited in the design of protocols that permit multiple-packet transmissions. In general, a potential tradeoff arises because the use of multiple-packet transmissions can increase the throughput, but it can also increase the delay. In certain situations, however, the delay is decreased with the use of reservations and multiple-packet transmissions, or at least the increase in delay is not too great.

Dramatic improvements in the network throughput are seen compared to using a scheme that does not use reservations and only includes one packet in each transmission. The reservation protocol reduces contention for a receiver in a multiple-hop network without using an elaborate scheduling scheme. Also, acquisition of a transmission can represent a significant overhead and grouping multiple packets reduces the overhead per packet. Finally, the capture feature of spread-spectrum signaling allows reservation transmissions to be made without causing destructive interference to other transmissions that are in progress.

Technology transfer

TSI has been involved in technology transfer in a number of different ways. TSI participated in ITT's SINCGARS SIP. The least-resistance routing (LRR) protocol that we have developed has been implemented in ITT's simulation of a SINCGARS packet radio network and LRR has been shown to be the best routing protocol among the approaches considered in ITT's particular packet radio network design. ITT was a subcontractor on the Phase II contract and is the manufacturer of the SINCGARS radio. Furthermore, TSI is participating in an ITT lead effort for CECOM's Near-Term Digital Radio (NTDR), and LRR and other TSI protocols are included in the system design. Based on results from the ARO contract, TSI and ITT worked jointly on a contract for Rome Labs that investigated waveform and channel access issues. A description of LRR was included in a chapter on routing for packet radio networks in "Routing in Communications Networks" (M. Steenstrup, editor, Prentice Hall: 1995).

TSI is participating with Clemson University, ITT, and InterDigital on a Focused Research Initiative program entitled "Research on wireless, mobile, distributed multimedia communication networks". One of major research objectives of the project is to extend LRR for routing multimedia messages. Also, TSI has submitted a proposal to ARPA to develop and implement the protocols that were researched and designed during the ARO Phase II contract. The goal of the proposed work to ARPA is to implement the network protocols in a form that can be utilized by simulations of packet radio networks and by actual radio hardware. This will produce software that allows DoD laboratories and DoD contractors to test the protocols developed by TSI and to incorporate the appropriate protocols into specific radio network designs.

TSI personnel have also discussed with Paul Sass of U.S. Army CECOM the possible use of the LRR protocol and other TSI protocols in future SINCGARS packet radio networks. In addition, TSI is in the preliminary stages of planning joint work with Clemson University to develop protocols for direct-sequence spread-spectrum packet radio networks for military applications.

List of publications

[1] M. B. Pursley, "New approaches for error correction in frequency-hop spread-spectrum receivers," *IEEE Second International Symposium on Spread Spectrum Techniques and Applications* (ISSSTA'92) Yokohama, Japan, November 29-December 2, 1992, pp. S-2-3 to S-2-10.

[2] M. B. Pursley and H. B. Russell, "Adaptive forwarding in frequency-hop spread-spectrum packet radio networks with partial-band jamming," *IEEE Trans. Commun.*, pp. 613-620, April 1993.

[3] M. B. Pursley and H. B. Russell, "Routing in frequency-hop packet radio networks with partial-band jamming," *IEEE Trans. Commun.*, pp. 1117-1124, July 1993.

[4] M. B. Pursley, "The derivation and use of side information in frequency-hop spread spectrum," *IEICE Trans. Commun., Special Issue on Spread Spectrum* , pp. 814-824, Aug. 1993.

[5] M. B. Pursley and H. B. Russell, "Use of side information in frequency-hop packet radio network protocols," 1993 *IEEE Mil. Commun. Conf. Rec.*, pp. 551-555, October 1993.
[6] M. B. Pursley and H. B. Russell, "Network protocols for frequency-hop packet radios with decoder side information," *IEEE Journal on Selected Areas in Communications*, pp. 612-621, May 1994.
[7] M. B. Pursley and H. B. Russell, "Multiple-packet forwarding protocols for frequency-hop packet radio networks," *Proc. Tactical Commun. Conf.*, pp. 371-378, May 1994.
[8] M. B. Pursley and H. B. Russell, "Frequency-hop signaling and multiple packets per transmission for store and forward packet radio networks," *IEEE Mil. Commun. Conf. Rec.*, pp. 168-172, October 1994.
[9] M. B. Pursley, "Reed-Solomon codes in frequency-hop communications," In *Reed-Solomon Codes and Their Applications*, S. Wicker and V. Bhargava, eds., IEEE Press: New York, 1994, pp. 150-174.
[10] M. B. Pursley and H. B. Russell, "Recognizing and responding to reduced-quality links in FH packet radio networks," to appear in the *IEEE Mil. Commun. Conf. Rec.*, Nov. 1995.
[11] M. B. Pursley and H. B. Russell, "Multiple-packet forwarding protocols for frequency-hop packet radio networks," to appear in the *International Journal of Wireless Information Networks*., Jan. 1996.
[12] D. L. Noneaker and C. D. Frank, "Design criteria for trellis codes with fading channels and finite interleaving depth," in preparation for journal submission.

Scientific personnel supported by contract

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